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COST-EFFECTIVE PRETREATMENT PROGRAMS

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ABSTRACT: A method is developed for planning cost-effective control programs for toxic pollutants in municipal treatment systems. It chooses the levels of industrial pretreatment and type of municipal sewage treatment a city can use so that all applicable standards and criteria on sewer discharges, receiving water quality, and municipal sludge quality are met at minimum cost. The problem is formulated as a nonlinear 0-1 integer programming model. An implicit enumeration procedure is developed for its solution. The method is applied to control of five heavy metals in Kokomo, Ind. The economic impact of EPA's national pretreatment policies and alternative water quality goals is studied.

INTRODUCTION

The Clean Water Act of 1977 (2), and the NRDC-EPA Consent Decree (9) have generated a great deal of concern over controlling toxic contaminants in industrial and municipal wastewaters. The U.S. Environmental Protection Agency (EPA) is in the process of establishing national technology-based effluent limits for direct industrial dischargers to publicly-owned treatment works (POTW's). A National Pretreatment Strategy has been developed by EPA (7) which requires local POTW's and State NPDES agencies to develop and administer pretreatment programs to prevent the interference or pass-through of toxic materials in the POTW. Criteria are also being developed to determine acceptable levels of toxic pollutants in receiving waters (11) and municipal sludges (3).

A rational control strategy for toxic pollutants should attempt to achieve a desired level of protection for the POTW and the receiving environmental media with a minimum expenditure of resources. Satisfaction of additional criteria concerning energy utilization, recycling of wastewater and sludges, and equitable distribution of costs and benefits may also be important. A strict reliance on technology-based pretreatment standards applied across broad industrial categories may fall short of meeting any of these goals in an optimal manner.

Control of toxic pollutants can be affected at two points within a municipal system, at the industrial source itself or at the POTW. The EPA Pretreatment

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Regulations recognize this by allowing industrial pretreatment standards to be relaxed to the extent that removal is achieved at the POTW and by requiring that stricter standards be set in those cases where water quality or sludge disposal criteria cannot be met. It seems reasonable, therefore, to try to coordinate individual industrial and POTW treatment efforts in the most cost-effective way possible.

This paper develops a methodology for planning cost-effective, integrated industrial-municipal pretreatment programs. It uses a mathematical programming approach to determing what levels of industrial pretreatment and POTW treatment in a given municipality will meet all relevant environmental criteria and standards at minimum total cost. It can be used to provide a quantitative framework for exploring such questions as the following:

1. What are the economic implications of enforcing or relaxing national pretreatment standards on industrial dischargers.
2. How can the total industrial pretreatment requirement be most cost-effectively distributed among a POTW's industrial sources.
3. Which pollutants are the critical ones in regards to maintaining receiving media quality criteria.
4. What are the economic implications of either strengthening or weakening these criteria.
5. Can it be more economical to have the POTW assume more of a treatment role while relaxing some of industry's responsibility.

The methodology does not directly address other important regulatory issues. These include impacts from combined sewer overflows, monitoring requirements, financial equity, and institutional arrangements. Therefore, its most valuable use will be as an informative first step in analyzing local pretreatment problems to generate understanding and insight that can then be applied to a more comprehensive analysis.

The following sections of this paper develop a mathematical formulation of the methodology and outline a solution procedure. An illustrative application to controlling heavy metals in Kokomo, Indiana is used to explore several of the economic issues cited previously. Finally some practical considerations in utilizing the methodology for actual decision making are studied.

Methodology

Formulation.—Fig. 1 is a conceptual diagram of a typical municipal sewer district. It contains a number of controllable industrial discharge sources and one additional source representing the lumped contribution of all uncontrollable sources. Each controllable source may have several alternative modes or levels of pretreatment that can be applied. These may consist of end-of-pipe treatment, production process modifications, or no pretreatment at all. All wastewater flows enter the POTW, which also has a variety of treatment options that may be employed. Estimates are assumed to be available on the costs and effluent quality associated with each industrial pretreatment and POTW treatment option. The problem then is to determine which combination of treatment options will meet

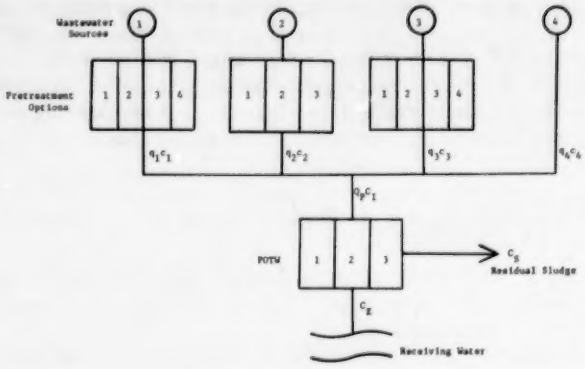

FIG. 1.—Conceptual Diagram of Typical Municipal Sewer District

all applicable environmental criteria and standards at least total cost.

Several different types of environmental protection requirements may be applicable to the waste flows in this system. Industrial sources may be subject to local or national categorical pretreatment standards on their discharges. For a particular pollutant, these can be written as

$$\frac{c_i C_E}{C_I} \leq \alpha_i \quad \ldots\ldots (1)$$

in which c_i = concentration of pollutant in discharge from source i; C_E = POTW final effluent concentration of pollutant; C_I = POTW influent concentration of pollutant; and α_i = pretreatment concentration standard applicable to the discharge from source i. The factor C_E/C_I represents the POTW removal credit allowed for in EPA's Pretreatment Regulations (7). For local standards, the credit may not be applicable.

A second type of environmental constraint may apply to the POTW's effluent quality or to the receiving water quality after sufficient mixing with the POTW effluent occurs. It can be written as

$$C_E \leq \frac{\beta}{d} \quad \ldots\ldots (2)$$

in which d = a dilution factor; and β = either an effluent discharge limit or a receiving water concentration criterion for some pollutant of interest. If β is the former, such as might appear in a POTW's NPDES Discharge Permit, then d would equal one. If β is a receiving water criterion, then d might represent the ratio of the POTW flow to the receiving water flow under some critical flow condition.

With some additional assumptions, d can be specified so that the water quality criterion, β, is met at least some stipulated percent of the time. These assumptions are the following: (1) The variation in daily average POTW flow is small compared with the variation in daily average receiving water flow; (2) the daily

average receiving water flow is lognormally distributed with mean, Q_R, and coefficient of variation, ν_R; (3) the daily average concentration of the pollutant of interest in the POTW final effluent is lognormally distributed with mean, C_E, and coefficient of variation, ν_E; and (4) either the pollutant of interest is absent in the receiving water upstream of the POTW, or β represents its maximum allowable increase to the receiving water's concentration. Then d can be specified as

$$d = \frac{Q_P}{Q_R}\left(\frac{(1+\nu_R^2)}{(1+\nu_E^2)}\right)^{0.5} \exp\{F_p[\ln(1+\nu_R^2)(1+\nu_E^2)]^{0.5}\} \quad \ldots\ldots (3)$$

in which Q_P = POTW flow; and F_p = standard normal cumulative deviate for the stipulated frequency of compliance with the criterion. (See Appendix I for the derivation of this expression.)

A third type of environmental constraint can be attached to the quality of the POTW sludge, i.e.

$$C_S \le \gamma \quad \ldots\ldots (4)$$

in which C_S = concentration of pollutant in POTW sludge (mass of pollutant per mass of sludge); and γ = sludge concentration limit. The value of γ may change with different types of POTW treatment and sludge disposal strategies. For strategies employing land application of sludge, limits on acceptable sludge quality are often given in terms of mass of pollutant applied annually per unit of land area. The equivalent sludge concentration limit can be obtained by dividing by the annual sludge application rate. This rate should be specified as part of the definition of the type of POTW treatment being considered.

The sewerage system in Fig. 1 is also subject to a set of flow balances, mass balances, and POTW removal relationships for the waste constituents being considered. For a specified set of pretreatment choices at each source, the POTW flow and influent concentration for a given pollutant can be computed as

$$Q_P = \sum_{i=1}^{N} q_i \quad \ldots\ldots (5)$$

$$C_I = \frac{\sum_{i=1}^{N} q_i c_i}{Q_P} \quad \ldots\ldots (6)$$

in which q_i = flow discharged by source i; and N = total number of sources. Eq. 6 assumes that there is no loss of material in the sewer system. If such losses are known to occur and can be quantified, then Eq. 6 should be modified accordingly.

It is assumed that the removal of a pollutant of interest in POTW treatment scheme of a specified type can be empirically established or estimated from the literature. This removal may be a function of the influent concentration seen by the POTW. Thus, one can write

$$C_E = f(C_I) \quad \ldots\ldots (7)$$

in which f = some known functional relation. If it is also possible to empirically

determine a sludge retention factor for the pollutant (i.e., the fraction of the pollutant removal that is incorporated into the POTW sludge), then the POTW sludge concentration can be written as

$$C_S = \frac{(C_I - C_E)r}{y} \quad \ldots\ldots (8)$$

in which r = sludge retention factor; and y = sludge production factor (i.e., the mass of POTW sludge produced per unit of waste flow treated).

Finally, the cost of a particular combination of pretreatment and POTW choices can be expressed as

$$V = \sum_{i=1}^{N} v_i + v_{\text{POTW}} \quad \ldots\ldots (9)$$

in which V = total system cost; v_i = cost of the pretreatment option used at source i; and v_{POTW} = cost of the treatment strategy used at the POTW. All quantities in Eqs. 1–9 should be expressed in a consistent set of units. Treatment costs should be in present worth dollars or equivalent annual costs and should account for both capital, and operation and maintainence costs. Flows and concentrations should be referenced to a consistent time period of averaging such as a long-term mean or an n-day average.

Solution Procedure.—The pretreatment problem, as previously stated, has the formal structure of a nonlinear 0-1 integer programming model. In this model, each pretreatment and POTW treatment option is represented with a variable whose value is 1 if the option is used in a solution and is 0 otherwise. If there are L possible POTW treatment options, and J_i possible pretreatment options at source i, then there are $L\left(\prod_{i=1}^{N} J_i\right)$ different combinations of system-wide treatment strategies. An evaluation of each combination to find the one that meets Eqs. 1, 2, and 4 at least cost would impose severe computational burdens on all but the smallest sized problems. A more efficient procedure for identifying an optimal solution is available through the technique of implicit enumeration, a special form of the branch and bound method of integer programming (6). A general purpose integer programming software package cannot be readily applied to the model because of the nonlinearities present in Eqs. 1, 6, and 7. Instead, a special purpose implicit enumeration solution procedure has been developed that exploits the particular structure of the pretreatment problem.

Throughout the procedure, a master list of the industrial sources is maintained. Sources are added or deleted from this list as the alogrithm progresses. The procedure begins by setting the optimal solution cost, V^*, to a very large number, fixing the POTW treatment choice to the lowest cost option, and designating the master source list as being empty.

At each stage of the procedure, the master source list is updated as follows: A candidate solution is formed consisting of the pretreatment choices already assigned to those sources on the list and the cheapest pretreatment options available to those sources not on the list. This solution is evaluated with respect to its cost, V, and its feasibility in the environmental quality conditions expressed by Eqs. 1, 2, and 4. Depending on the result of this evaluation, the following steps are taken:

1. If $V \geq V^*$, then no further additions of sources to the master list will result in a lower cost solution. In this case, the last source added to the list is removed and the pretreatment choice of some other source on the list is assigned to its next higher cost level.
2. If $V < V^*$, and the candidate solution is feasible, then it becomes the new incumbent optimal solution and the master list is updated as in the previous section.
3. If $V < V^*$, but the candidate solution is infeasible, then the following test is made. If the use of the highest levels of pretreatment by all sources not on the master list will still not make the candidate solution feasible, then the pretreatment choice for some source on the list is raised to its next higher cost level. Otherwise, a new source is added to the list with its pretreatment choice set at its cheapest available option.

After the master list has been updated in this fashion, a new candidate solution is formed and the next stage of the algorithm begins. When some source on the list must be chosen for treatment level upgrading, a last in, first out (LIFO) rule is used. If the chosen source is already treating to its most expensive level, it is removed from the list and another source is selected. When no more sources remain on the list, the next higher cost POTW treatment option is then used to form candidate solutions with. After all POTW options have been exhausted, the algorithm terminates.

When a new source must be added to the master list, it is chosen in the following manner: For each source i not currently on the list, define η_{ik} as the difference in source discharge concentration of pollutant k between the cheapest pretreatment option and the option with the lowest discharge concentration of that pollutant at source i. Then set

$$\eta_i = \sum_{k \in K_v} \eta_{ik} \quad \ldots\ldots\ldots\

ber of sources and number of pretreatment options at each that have some effect on constraints of type shown by Eqs. 2 or 4. Since this is a combinatorial problem, one would expect the search effort to increase exponentially as a function of these measures of problem size. The number of pollutants considered would not affect seriously the search effort, and the number of POTW treatment options used would, at worst, make the computation time increase at a linear rate.

The test problem used a varying number of sources whose flows were obtained from a table of random numbers. Each source was capable of using four different pretreatment options. A single pollutant and POTW treatment option was used. The cost of each pretreatment option was set equal to a function of the level of treatment and the amount of source flow. The POTW effluent limit was taken as 25% of the untreated source loading. No removal across the POTW was assumed and no pretreatment standards or sludge criteria were imposed on this test problem.

The solution procedure has been coded in FORTRAN and implemented on a DEC PDP-11/70 computer. Fig. 2 shows the computer time, in seconds, required to solve the test problem as the number of sources was increased. As expected, an exponential increase in solution time is observed. Beyond 14 sources (each with four pretreatment options), the computational efficacy of the method becomes doubtful. However, the solution times observed here are not at all out of line with those experienced on other types of 0-1 integer programs of similar size. As a point of reference, the test problem with 14 sources contains 56 0-1 variables and over 268,000,000 alternative solutions.

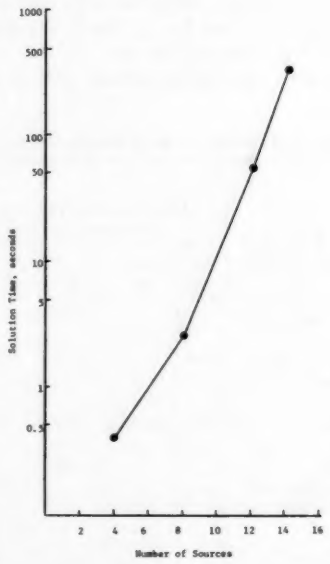

FIG. 2.—Solution Times for Test Problem

Application

Study Area.—Kokomo, Indiana is a city of approximately 42,000 people and contains a sizeable number of metal fabricating and finishing industries. It is served by an activated sludge, dual media filtration sewage treatment plant that discharges to Wildcat Creek. During 1978–79, an EPA funded study sampled the industrial and residential sources of heavy metals entering the Kokomo sewer system (12). A 60 day sampling of heavy metals at the POTW was also conducted (8). The data from these studies were used to analyze several aspects of heavy metals control in the Kokomo treatment system.

The metals of concern were cadmium, chromium, copper, nickel, and zinc. Table 1 lists the source contributions of these metals associated with the "existing" conditions (1978–79) in Kokomo. Industrial sources are seen to have accounted for 28% of the flow, 96% of the cadmium, 99% of the chromium, 70% of the copper, 67% of the nickel, and 98% of the zinc that entered the POTW.

Four types of end-of-pipe pretreatment, where appropriate, at each source, and three types of POTW treatment, were considered. Table 2 briefly describes each type. For this analysis it was assumed that Kokomo's POTW had not yet installed its filters. The effluent quality associated with pretreatment option B and C were derived from operating data presented in Ref. 4. Percent removals, sludge production, and daily effluent variability for POTW options I and II were based on the data collected from the Kokomo plant (8). For option III, an assumed set of very low level effluent concentrations was used. The cost of the pretreatment options at the various sources were estimated using data from Ref. 4. The costs of POTW treatment were taken from Ref. 1. The flow statistics of Wildcat Creek were supplied by the U.S. Geological Survey.

It was assumed that EPA's published national pretreatment standards for the

TABLE 1.—Existing Sources of Heavy Metals in Kokomo (1978–79)

Source (1)	Existing pretreatment (2)	Mean Discharge Concentration, in micrograms per liter					Mean flow, in cubic meters per second (8)
		Cd (3)	Cr (4)	Cu (5)	Ni (6)	Zn (7)	
1. Electroplating	pH adjustment, settling	30		1,000			0.019
2. Semiconductors	pH adjustment, settling	50		320	50	2,200	0.074
3. Electroplating	None		11,000			23,000	0.0041
4. Electroplating	None	290	42,000	490	2,400	1,100	0.011
5. Steel Wire	Settling					162,000	0.017
6. Galvanizing	None			2,400		63,000	0.0032
7. Metal Forming	pH adjustment, settling				3,000		0.015
8. Metal Fabrication	None					1,900	0.0025
9. Laundry Service	None					510	0.0017
10. Printing	None		3,200	7,500			0.0079
11. All others	—	1	15	135	98	172	0.37

TABLE 2.—Alternative Treatment Options

Treatment Code (1)	Description (2)	Mean Effluent Concentration or Percent Removal				
		Cd (3)	Cr (4)	Cu (5)	Ni (6)	Zn (7)
Industrial A[a]	Existing treatment					
Industrial B[b]	pH adjustment, settling, Cr reduction (if applicable)	10 μg/L	600 μg/L	800 μg/L	940 μg/L	550 μg/L
Industrial C[b]	Filtration added to B	10 μg/L	300 μg/L	400 μg/L	550 μg/L	250 μg/L
Industrial D	Zero discharge (ion exchange added to C)	0 μg/L	0 μg/L	0 μg/L	0 μg/L	0 μg/L
POTW I	Existing secondary	78%	95%	80%	13%	85%
POTW II	Filters added to I	87%	98%	88%	27%	91%
POTW III	Two stage high lime treatment added to I	2 μg/L	10 μg/L	10 μg/L	50 μg/L	50 μg/L

[a]See Table 1 for effluent quality.
[b]Actual source effluent quality is minimum of entry here and in Table 1.

electroplating source category (5) would apply to all sources. Pretreatment standards for the nonplating sources in Kokomo have not been established yet. However, because these standards are supposed to be technology-based and the same technology for metals removal is applicable to all of Kokomo's industrial sources, this assumption appears reasonable.

Two different sets of receiving water quality criteria were considered. The first was based on EPA's published 24 hr average limits for the protection of aquatic life (11). The second, less stringent set, came from the Illinois Environmental Protection Agency's (IEPA) General Water Quality Standards (10). The two sets are compared in Table 3. A sludge criterion of 12.5 mg/kg on cadmium was also introduced. It is assumed that the POTW would like to apply its sludge at an annual rate of 40 Mtons/ha to cropland on which the EPA limit of 0.5 kg/ha per year of cadmium applies (3). The application rate of 40 Mtons/ha is a typical figure for municipal sludge based on satisfying plant nitrogen requirements.

Results.—The first issue explored was the effect that EPA pretreatment standards and sludge criteria had on the costs of meeting the EPA water quality criteria. Four runs of the pretreatment planning methodology were made. In Run 1, all pretreatment standards were enforced, POTW removal credits were allowed, and no sludge criteria were imposed. Run 2 was similar to Run 1 except that POTW removal credits were not allowed. In Run 3, the pretreatment standards were dropped. Run 4 added the POTW sludge limit on cadmium to the conditions of Run 1. Each run was required to satisfy the EPA water quality criteria on average (50% of the time) in Wildcat Creek ($F_p = 0$ in Eq. 3).

The resulting least-cost pretreatment plans are shown in Table 4. Column 9

TABLE 3.—Water Quality Criteria

Parameter (1)	U.S. EPA Criteria, in micrograms per liter (2)	Illinois EPA Criteria, in micrograms per liter (3)
Cadmium	1.3	50
Chromium	1,537	1,000
Copper	4.5	20
Nickel	76	1,000
Zinc	68	1,000

Note: U.S. EPA criteria are based on a water hardness of 200 mg/L.

shows none of the plans found it cost-effective to substitute increased POTW treatment for less industrial pretreatment. As might be expected, the use of uniform pretreatment standards resulted in a more expensive plan than was necessary to meet simply the water quality criteria. Run 3 indicates that pretreatment standards could have been dropped for sources 3 and 7 without violating the water quality criteria. The cost savings are 28% when compared with the case of uniform standards without POTW removal credits, or 18% when the credits are permitted. Use of the POTW removal credits helped make the uniform pretreatment standards approach more cost-effective by 12%. However, inspection of Run 2 shows that only sources 2 and 8 benefited from receiving the credits. The effect of adding the cadmium sludge criterion in Run 4 was felt only by source 2 whose costs were raised by 8%.

In all of these runs, the critical receiving water quality parameter was copper. Two sources, 4 and 10, were always required to attain zero discharge so that the EPA copper criterion could be met on average in Wildcat Creek. Even if all of the copper from industrial sources was eliminated, the contribution from the uncontrollable nonindustrial sector would cause violation of the EPA limit 36% of the time under secondary treatment at the POTW, and about 22% of the time under either of the tertiary POTW alternatives.

TABLE 4.—Least-Cost Pretreatment Plans

Run (1)	Uniform pretreatment standards (2)	Cd sludge criterion (3)	POTW removal credits (4)	Water quality criteria (5)	Reliability level, as a percentage (6)	Total cost, in thousands of dollars per year (7)	Industrial treatment choices for sources 1–10 (8)	POTW treatment choice (9)
1	Yes	No	Yes	EPA	50	320.7	C A B D B B B A A D	I
2	Yes	No	No	EPA	50	364.4	C B B D B B B B A D	I
3	No	No	No	EPA	50	262.3	C A A D B B A A A D	I
4	Yes	Yes	Yes	EPA	50	347.2	C B B D B B B A A D	I
5	Yes	Yes	Yes	IEPA	80	218.7	B B B B B B B A A B	I
6	Yes	Yes	Yes	IEPA	85	248.9	C B B B B B B A A B	I
7	Yes	Yes	Yes	IEPA	90	668.7	B B B B B B B A A B	II
8	Yes	Yes	Yes	IEPA	95	1,652.3	B B B B B B A A A A	III

Note: Treatment codes are defined in Table 2.

A second set of four runs was made to observe how the least-cost pretreatment plans changed as the reliability level in meeting water quality criteria was increased. Because the strict EPA criterion on copper severely constrained the choice of treatment options, the more lenient Illinois EPA criteria were used. The same conditions as in Run 4 were also imposed. Table 4 presents the results obtained for meeting the Illinois criteria in Wildcat Creek 80, 85, 90, and 95% of the time (Runs 5–8, respectively).

One interesting feature of these results is how an increased level of POTW treatment became cost-effective when the reliability level reached 90%. Once again, it was copper that was the controlling water quality parameter. Under the Illinois criteria, an 85% reliability level (Run 6) can be attained at less cost than a 50% level under the EPA criteria (Run 4). It is also evident that to obtain higher fixed increments of reliability, increasingly larger incremental costs must be expended. Results such as these can help serve as a basis for making intelligent trade-offs between the cost of pollution control, the benefits associated with receiving water quality, and the reliability of attaining those benefits.

Analysis

The methodology described in this paper allows a city's pretreatment requirements to be matched to local conditions. The total reduction in a pollutant's loading is determined by the need to meet receiving media quality criteria. This load reduction is then distributed among the various controllable sources and the POTW on the basis of cost-effectiveness, i.e. the first to treat are those who can treat most cheaply. National or local pretreatment standards, should they be applicable, are considered as side conditions. Use of the methodology can actually suggest new sets of local pretreatment standards that will meet environmental goals on a cost-effective basis, such as was obtained in the Kokomo case study.

The criterion of minimizing total system treatment cost assumes a desire for economic efficiency for society as a whole. This may conflict with the POTW's desire to minimize its own cost by having industry pretreat to the fullest extent required. Also, it may conflict with industry's desire to remove all pretreatment requirements. However, it is assumed that any additional treatment costs incurred by the POTW in a least-cost plan can be passed on to its industrial customers in the form of user charges.

Cost-effective pretreatment plans can require different levels of pretreatment from sources classified within the same industrial category. This may lead to charges of unfair treatment by sources required to use more pretreatment than their competitors and may impede implementation of the plan. This argument has another side to it, though. When discharge concentrations of a critical pollutant are similar between sources in the same industrial category, the cost-effective plan tends to require higher levels of pretreatment from the larger sources. This is due to their larger contribution to the pollutant's total loading and their lower costs per unit of waste treated because of economies of scale. Thus, on a cost per unit of flow or production output basis, the disparities between sources may be less under the least-cost plan than under a plan requiring a uniform level of pretreatment.

If so desired, the methodology can accomodate a requirement that sources

within the same category provide a uniform level of pretreatment. These sources should be replaced with one equivalent source whose flow, effluent quality, and cost for each pretreatment option considered is found by combining the values associated with its member sources. For very large systems, some source consolidation of this type will be needed to insure that the dimensions of the problem do not exceed a size that can be solved in a reasonable amount of computer time by the branch and bound procedure.

The methodology requires input data regarding the source strength and removeability characteristics of the pollutants of interest for a variety of industries, POTW's and treatment technologies. Because of the discrete nature of the 0-1 integer programming model, small changes in the input data may cause rather large changes in the form that the least-cost control policy takes. Data sensitivity analyses can be made to assess the magnitude and importance of such behavior, especially with respect to those data whose values are most uncertain. This will produce more confidence and credibility for the method's output and perhaps identify areas where more data collection would provide maximum informational benefits.

Conclusions

The problem of cost-effective control of toxic pollutants in municipal treatment systems can be formulated as a nonlinear 0-1 integer program. An implicit enumeration procedure that exploits the special structure of the problem can be used for its solution. Systems with up to 14 controllable sources of some critical pollutant, each having four alternative pretreatment options, have been solved in 6 min or less of computer time. Larger size problems might require some consolidation of sources into equivalent, uniform pretreatment source categories to make the methodology computationally practical.

An analysis of heavy metals control in Kokomo, Indiana showed that use of national standards as a minimum pretreatment requirement was less cost-effective than a policy based on no minimum standards. The use of POTW removal credits helped improve the cost efficiency of the minimum national standards policy. Copper was found to be the critical parameter for meeting water quality criteria in Wildcat Creek. It may not be technically feasible for Kokomo to meet EPA's suggested copper limit at daily frequencies in excess of 80%. Under Illinois' less stringent water quality criteria, it was possible to substitute economically increased POTW treatment for industrial pretreatment as the required frequency of criteria compliance increased.

Certain aspects of the least-cost treatment programs derived by the methodology may require attention if their implementation is considered. In cases where additional treatment at the POTW is indicated, industrial cost recovery programs may need to be developed. Resolution of questions of equity arising when a program asks that similar industries provide different levels of pretreatment may be required before implementation can become feasible. Additional data gathering efforts and sensitivity studies may be needed to produce results with acceptable confidence limits. Regardless of whether or not its output is actually implemented, use of the methodology should provide a more rational and quantitative understanding of local problems related to controlling toxic pollutants.

Appendix I.—Derivation of Critical Dilution Factor Expression

After complete mixing of the POTW discharge with a receiving water, the resulting concentration of a pollutant of interest, c_R, can be written as

$$c_R = \frac{c_E Q_P}{q_R} \quad \ldots\ldots (11)$$

in which c_E = daily POTW effluent concentration; Q_P = daily POTW discharge flow rate; and q_R = daily receiving water flow rate downstream of the discharge. This expression assumes that the pollutant is not present in the receiving water upstream of the POTW. Also assume that c_E and q_R are independent and log-normally distributed random variables and that Q_P is constant.

By log transforming (Eq. 11) one obtains

$$\ln(c_R) = \ln(c_E) + \ln(Q_P) - \ln(q_R) \quad \ldots\ldots (12)$$

in which now the quantities $\ln(c_E)$ and $\ln(q_R)$ are normally distributed. Since a linear combination of normally distributed variables is also normal, it follows that $\ln(c_R)$ is normally distributed. If the mean values of c_E and q_R are C_E and Q_R, respectively, and their coefficients of variation are ν_E and ν_R, respectively, then by the properties of the lognormal distribution, the mean, μ, and variance, σ^2, of $\ln(c_E)$ and $\ln(q_R)$ are

$$\mu_{cE} = \ln(C_E) - 0.5 \ln(1 + \nu_E^2) \quad \ldots\ldots (13)$$

$$\mu_{qR} = \ln(Q_R) - 0.5 \ln(1 + \nu_R^2) \quad \ldots\ldots (14)$$

$$\sigma_{cE}^2 = \ln(1 + \nu_E^2) \quad \ldots\ldots (15)$$

$$\sigma_{qR}^2 = \ln(1 + \nu_R^2) \quad \ldots\ldots (16)$$

Using the rules for finding the mean and variance of linear combinations of uncorrelated random variables, one obtains the mean and variance of $\ln(c_R)$ as

$$\mu_{cR} = \mu_{cE} + \ln(Q_P) - \mu_{qR} \quad \ldots\ldots (17)$$

$$\sigma_{cR}^2 = \sigma_{cE}^2 + \sigma_{qR}^2 \quad \ldots\ldots (18)$$

Now define the critical receiving water concentration, c_R^*, as that value of C_R not exceeded more than $100(1 - p)$ percent of the time. Because $\ln(c_R)$ is normally distributed

$$c_R^* = \exp(\mu_{cR} + F_p \sigma_{cR}) \quad \ldots\ldots (19)$$

in which F_p = the standard normal cumulative deviate for probability level, p. The critical dilution factor, d, can be defined as

$$d = \frac{c_R^*}{C_E} \quad \ldots\ldots (20)$$

Substitution of Eqs. 13–19 into Eq. 20 yields

$$d = \frac{Q_P}{Q_R} \left(\frac{(1 + \nu_R^2)}{(1 + \nu_E^2)} \right)^{0.5} \exp\{F_p [\ln(1 + \nu_R^2)(1 + \nu_E^2)]^{0.5}\} \quad \ldots\ldots (21)$$

Appendix II.—References

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Appendix III.—Notation

The following symbols are used in this paper:

C_E = mean pollutant concentration in POTW final effluent;
C_I = mean pollutant concentration in POTW influent;
C_S = mean pollutant concentration in POTW sludge;
c_i = mean pollutant concentration in discharge from source i;
c_E = pollutant concentration in POTW final effluent;
c_R = pollutant concentration in receiving water;
d = dilution factor;
F_p = standard normal cumulative deviate;
N = number of sources;
Q_P = POTW flow;
Q_R = mean receiving water flow;
q_i = mean flow discharged from source i;
q_R = receiving water flow;
r = POTW sludge retention factor;

v_i = cost of pretreatment at source i;
v_{POTW} = cost of treatment at POTW;
V = total system cost;
y = POTW sludge production factor;
α = pretreatment standard;
β = POTW effluent or receiving water quality criterion;
γ = POTW sludge quality criterion;
v_E = coefficient of variation of daily POTW effluent concentration;
v_R = coefficient of variation of daily receiving water flow;
μ = mean of log transformed variable; and
σ^2 = variance of log transformed variable.